AN EXPERIMENTAL INVESTIGATION INTO THE AUGMENTATION TO THERMAL ENERGY OUTPUT FROM A FLAT-PLATE COLLECTOR FITTED WITH A PLANAR-REFLECTOR

by

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AN EXPERIMENTAL INVESTIGATION INTO THE AUGMENTATION TO THERMAL ENERGY OUTPUT FROM A FLAT-PLATE COLLECTOR FITTED WITH A PLANAR-REFLECTOR

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CERTIFICATE

It is certified that the work contained in the thesis entitled **AN EXPERIMENTAL INVESTIGATION INTO THE AUGMENTATION TO THERMAL ENERGY OUTPUT FROM A FLAT-PLATE COLLECTOR FITTED WITH A PLANAR-REFLECTOR**, by Capt. Jackson Mathew, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Last but not the least the author would like to take this opportunity to convey his sincere thanks to his wife and son who bore stoically the vicissitudes of the present work with him.

- JACKSON MATHEW

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ABSTRACT

The thesis presents an experimental investigation into the augmentation to thermal energy output from a flat-plate collector, occurring as a result of attaching a planar-reflector to the flat-plate collector at its top edge. Further the enhancement of thermal energy with respect to the angle of tilt of the planar-reflector to the horizontal plane through its base, has also been studied. The increase in thermal energy output of 35 percent is achieved with the planar-reflector-collector combination. It is also observed that the optimum increase in output is obtained for a planar-reflector tilt angle of 80° to the horizontal. Since the data presented herein were collected here at Kanpur from December to January, the base flat-plate collector tilt angle was kept as 41° = latitude + 15°. The thesis also describes a reflector-collector set up for a year-round enhancement of the energy output involving a seasonal correction to the optimal tilt of the reflector-collector system.

CHAPTER I

INTRODUCTION

1.1 ENERGY CRISIS AND THE ALTERNATIVES

The known resources of fossil fuels in the world are depleting very fast and it is estimated that, by AD 2030, man will have to increasingly depend upon renewable sources of energy. Among the various energy alternatives, the nuclear and solar options stand out distinctly with their unique advantages. The other sources of energy alternatives are wind, Ocean (tidal, wave, thermal gradient) biomass, and geothermal. Water power is extensively exploited in most parts of the world, although in our country a lot remains to be tapped and the capacity could be increased by at least a factor of four.

While the fossil fuels are depleting the energy demand is increasing both on account of increase in population and standard of living. Also the indiscriminate use of commercial energy has led to serious environmental problems like air and water pollution.

The estimated energy reserves of all types in the world are given in Table 1.1.1 [1] . In a large developing country

Resources	Estimated recoverable amount	Resource base
Solar radiation at Earth's surface	1000 TW	90,000 TW
Wind	10 TW	1200 TW
Wave	0.5 TW	3 TW[d]
Tides	0.12 TW[a]	3 TW
Hydro	1.5 TW[a]	30 TW
Salinity gradients	—	3 TW
Geothermal flow	—	30 TW
Geothermal heat	50 TWy[a]	1.6×10^{11} TWy
Kinetic energy in atmospheric and oceanic circulation	—	32 TWy
Biomass (standing crop)	—	450 TWy[c]
Oil	300 TWy[a], 2500 TWy[b]	—
Natural gas	180 TTWy[a], 1400 TWy[b]	—
Coal	930 TWy[a], 7000 TWy[b]	—
Uranium-235	90 TWy[a]	
Other fission resources	10,000 TWy[b]	—
Deuterium fusion	3×10^{11} TWy[b]	—
Present rate of primary energy conversion	10 TW	—

[Source: Chessire and Pavitt (1978), Soresen (1979)]
Tera watt TW = 10^{12} W
TWy = Tera watt—year
a. Estimated recoverable
b. Ultimate recoverable
c. At present
d. Theoretical estimate

Table 1.1.1: Estimates of global Energy Resources.

like India, with a massive rural population, there is tremendous scope for renewable sources, such as solar energy, wind and biogas to meet the decentralized, requirements for lighting, heating, pumping and low grade heat. The large size of the country also provides a role for renewable energies in isolated and remote locations.

Fig. 1.1.1 shows the world wide annual solar radiation distribution. India receives as much as 700 kJ of solar radiation per year per sq cm of surface. Figs. 1.1.2 and 1.1.3 give the monthly averaged daily mean total solar radiation on a horizontal surface through out the world,for the months of January and July, respectively. India has an average of 500 cal cm^{-2} per day both in summer and winter which is comparatively a high value. Therefore, it is a favourable location for the year round solar applications and the role of solar energy is indeed going to be predominant.

India lies between the latitudes of 7° and 37°N. Approximate quantity of solar energy falling on India is 3000 trillion kWH per year, which is 3000 times the energy consumed by us as of today and 200 times the energy required in 2000 AD. There are between 250-300 days of useful sunshine per year in most parts of our country. Mean daily global solar radiation at various places in India is given in Table 1.1.2 [2].

ANNUAL GLOBAL RADIATION (R) IN KILOJOULES. $CM^{-2}.YEAR^{-1}$.

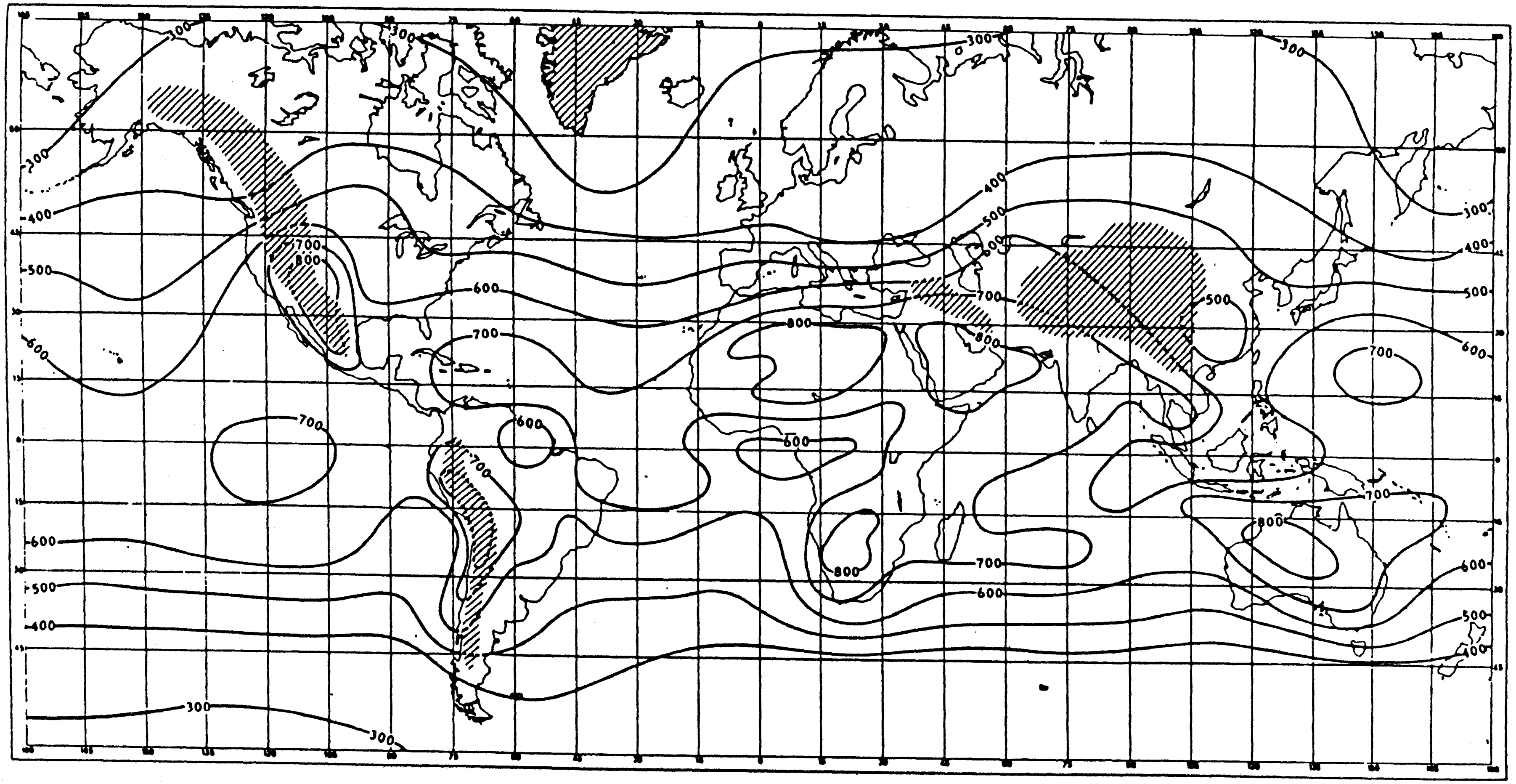


Fig. 1.1.1 Annual solar radiation distribution over the world.

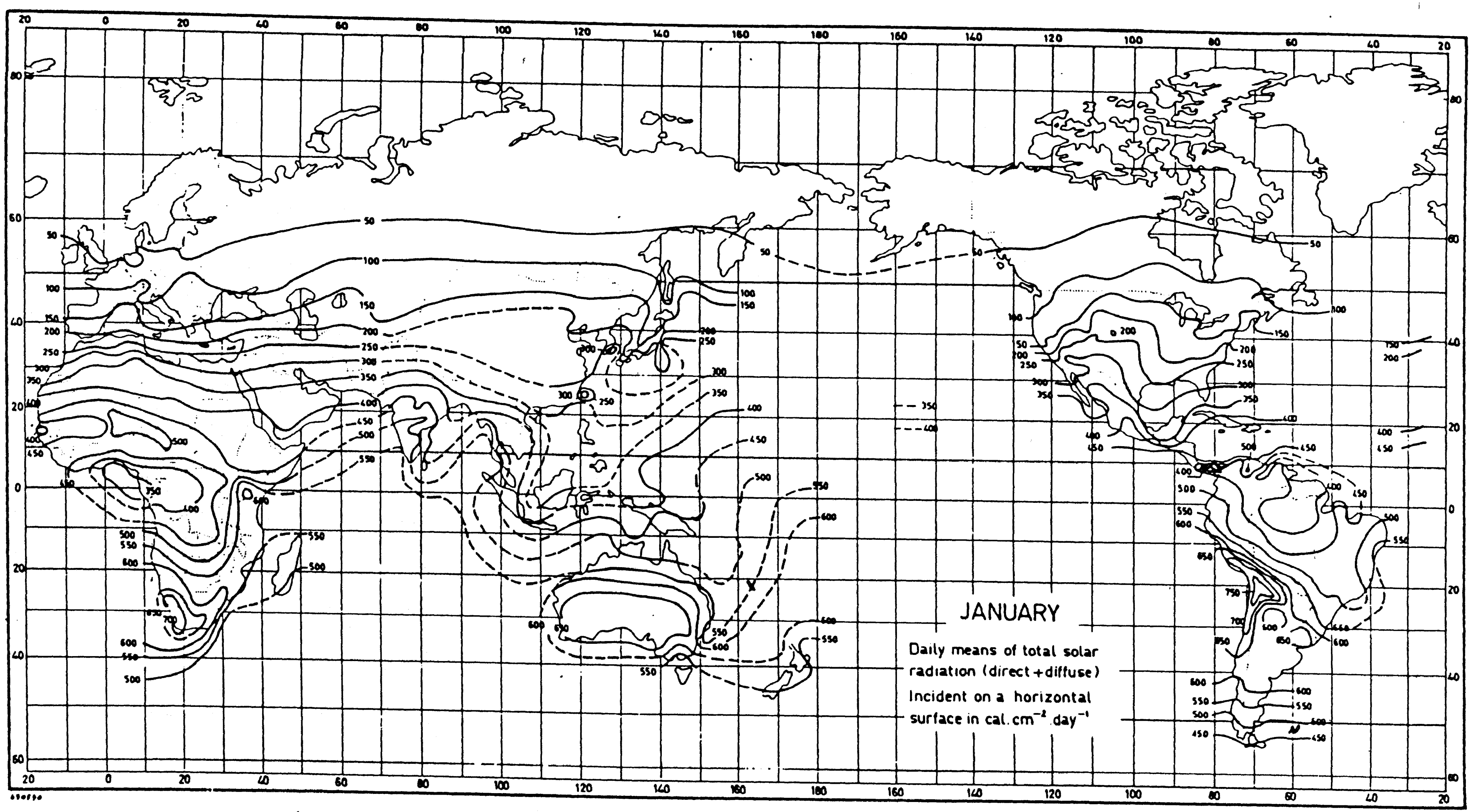


Fig. 1.1.2 Mean daily total solar radiation on a horizontal surface in January for the world.

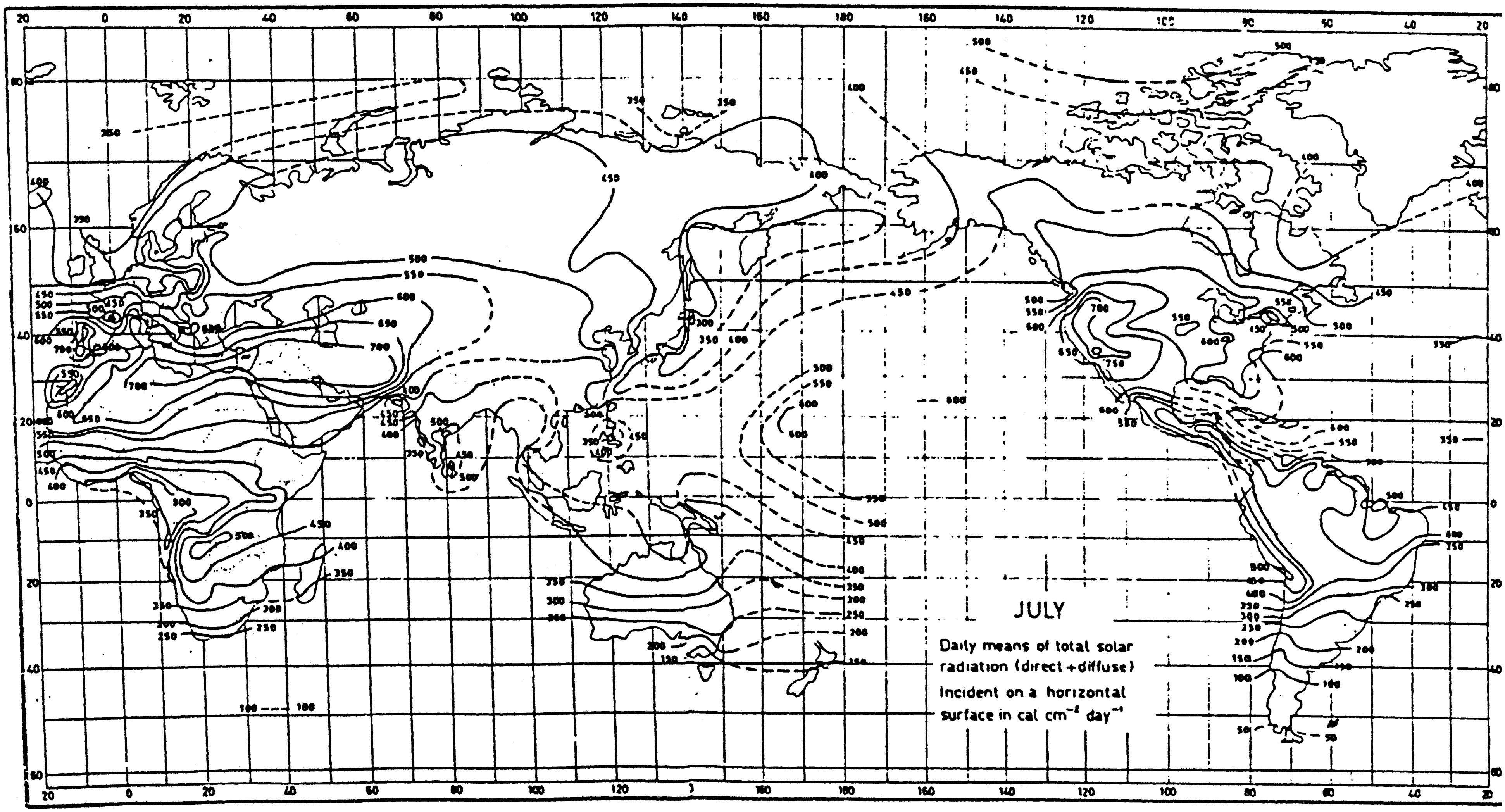


Fig. 1.1.3 Mean daily total solar radiation on a horizontal surface in July for the world.

Principal Station	*Data*	*Jan.*	*Feb.*	*March*	*April*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Mean*
Ahmedabad	1962-78	4·89	5·78	6·73	7·33	7·61	6·38	4·84	4·52	5·54	5·77	5·00	4·59	5·75
Bhavnagar	1967-78	5·14	5·96	6·86	7·26	7·60	6·03	4·62	4·30	5·46	5·90	5·22	4·78	5·76
Bombay	1969-78	5·03	5·75	6·44	6·99	7·26	5·17	4·06	3·97	4·87	5·44	5·07	4·79	5·40
Calcutta	1957-78	4·22	5·03	5·79	6·32	6·52	4·96	4·64	4·46	4·47	4·55	4·37	4·09	4·95
Goa	1963-78	5·68	6·37	6·75	6·92	6·73	4·78	3·99	4·75	5·30	5·61	5·61	5·38	5·66
Jodhpur	1960-78	4·71	5·56	6·54	7·23	7·54	7·06	5·97	5·54	6·10	5·82	4·90	4·43	5·95
Nagpur	1960-78	4·91	5·67	6·31	6·78	6·91	5·64	4·38	4·12	5·11	5·61	4·86	4·86	5·43
Madras	1957-78	5·23	6·29	6·88	6·92	6·53	5·82	5·40	5·57	5·71	5·84	4·34	4·27	5·73
New Delhi	1957-78	3·98	5·00	6·13	6·93	7·28	6·54	5·33	5·05	5·60	5·35	4·52	3·84	5·46
Pune	1957-78	5·30	6·17	6.81	7·15	7·30	5·88	4·53	4·57	5·30	5·66	5·23	4·92	5·75
Shillong	1967-78	4·00	5·07	5·63	5·70	5·23	4·11	4·25	4·21	3·86	4·02	3·94	4·14	4·51
Trivandrum	1959-78	5·93	6·35	6·68	6·16	5·49	5·25	5·02	5·55	5·94	5·23	4·95	5·13	5·64
Visakhapatnam	1961-78	5·37	6·08	6·50	6·66	6·67	5·17	4·66	4·94	5·16	5·28	5·16	5·06	5·56

Table 1.1.2: Mean daily global solar radiation in India kWh/m^2 day.

Domestic solar water heating is one of the popular and established solar energy applications. The technology for solar water heating is quite well developed and can readily be used to displace the conventional fuel usage. The army is mostly deployed in remote border areas, where no conventional sources of energy are available. In such areas, establishment of devices for tapping non-conventional energy, would greatly improve the living conditions of the soldiers. One such application could definitely be the solar water heating, especially in winter, and this encouraged me to take up this subject for my thesis work.

1.2 LITERATURE SURVEY

Water heating is commonly done with the help of simple flat-plate collectors. In winter, since the heating demand is high, planar reflectors have been suggested as an inexpensive means of increasing the heat collection by the flat-plate collector, to match the demand more closely. It is also the simplest method for boosting the solar flux incident on an absorbing surface.

There is a wide variety of means for increasing the flux radiation on receivers; they can be classified as lenses or reflectors by the types of mounting and orienting systems, by the concentration of radiation they are able to accomplish, by

materials of construction or by application. Figure 1.2.1 shows sections of several types of focusing reflector systems.

Figure 1.2.1 (A) shows a flat receiver with plane reflectors at the edges to reflect additional radiation onto the receiver. In this case some of the diffuse component of radiation incident on the reflector would also be absorbed at the receiver in addition to the beam component. Fig. 1.2.1(B) shows a conical system in which the receiver is cylindrical. Fig. 1.2.1(C) shows a parabolic system that lends itself to very high concentration ratios, which could in principle be used in applications where high temperatures are required. A modification to this is shown in Fig. 1.2.1(D) where an auxiliary or a secondary reflector is used in effect to shift the focus to a more convenient location. Other arrangements of secondary reflectors are also possible. A Fresnel reflector is shown in Fig. 1.2.1(E) and its refracting counterpart in 1.2.1(F). The individual plane or curved segments are each designed to reflect radiation to the receiver.

Higher concentration devices using only the beam component of solar radiation, can produce elevated operating temperatures under clear sky conditions, but require good optical components, more precise fabrication techniques, and generally a mechanism for tracking the sun. A planar-reflector augmented flat-plate collector is however, better at utilizing both diffuse and beam

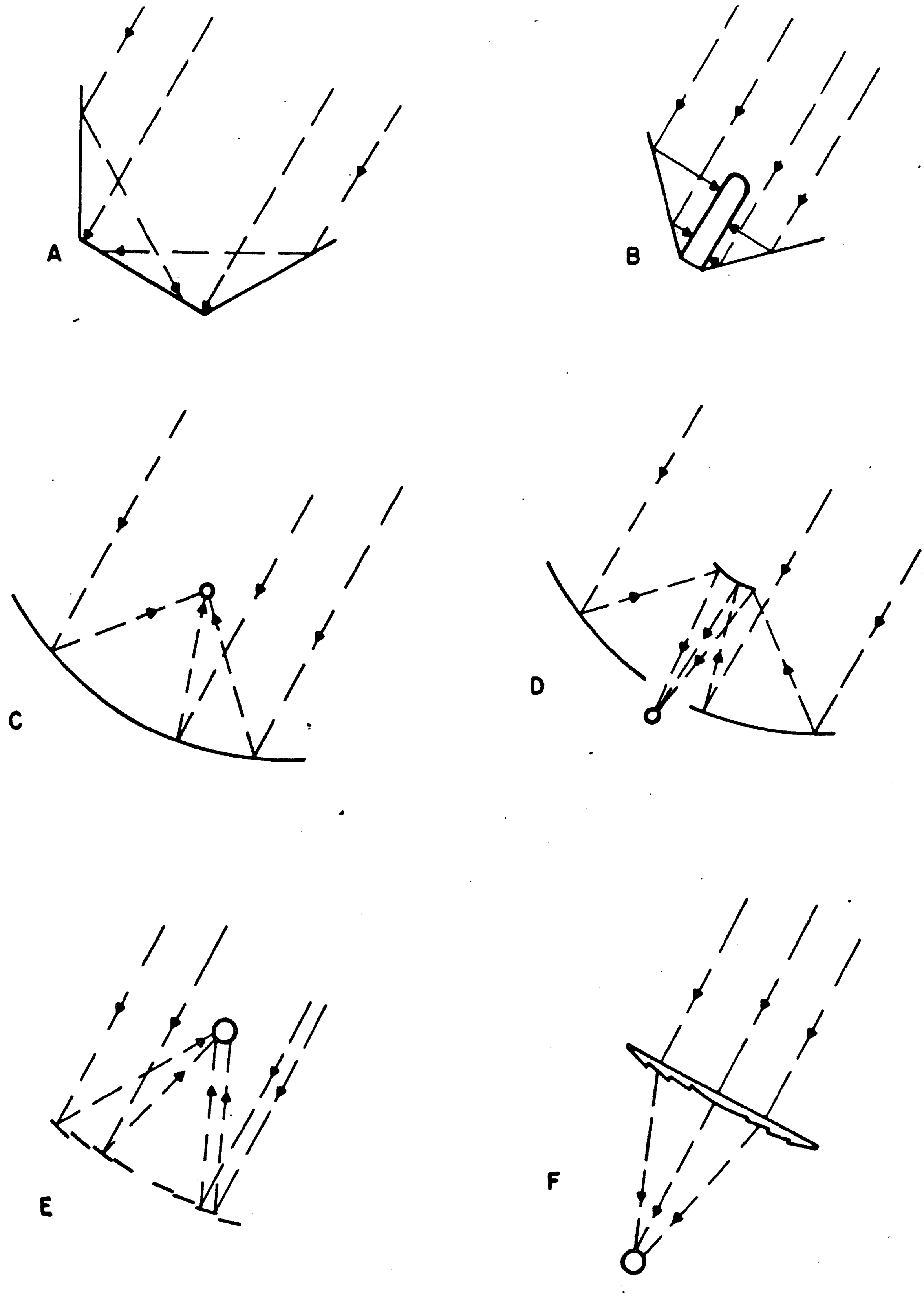


Fig. 1.2.1 Several types of focusing reflector systems.

radiations, while providing a moderate concentration with minimal tracking. Therefore for a large developing country like India, this simple method can be considered, to boost the solar flux incident on a flat-plate collector.

In the last two decades some work has been done on this topic especially in the USA and Australia. It has been proved that use of planar-reflective surfaces can substantially improve the performance of solar collectors. People have considered different models of planar-reflector-collector configurations for their study. Details of some of such models are explained below:

a. Chiam [8] used a planar-reflector-collector model as shown in Fig. 1.2.2 for his study. In this configuration, a single reflector is mounted above the collector. In the figure L_R denotes the length of the reflector, W_R denotes the width of the reflector, L_C denotes the length of the collector and W_C denotes the width of the collector. The collector is tilted at an angle β to face the equator, and the reflector is positioned at an angle ψ to the plane of the cover of the collector.

   It has been found that the principal parameters affecting the performance of the planar-reflector-receiver system are the reflector

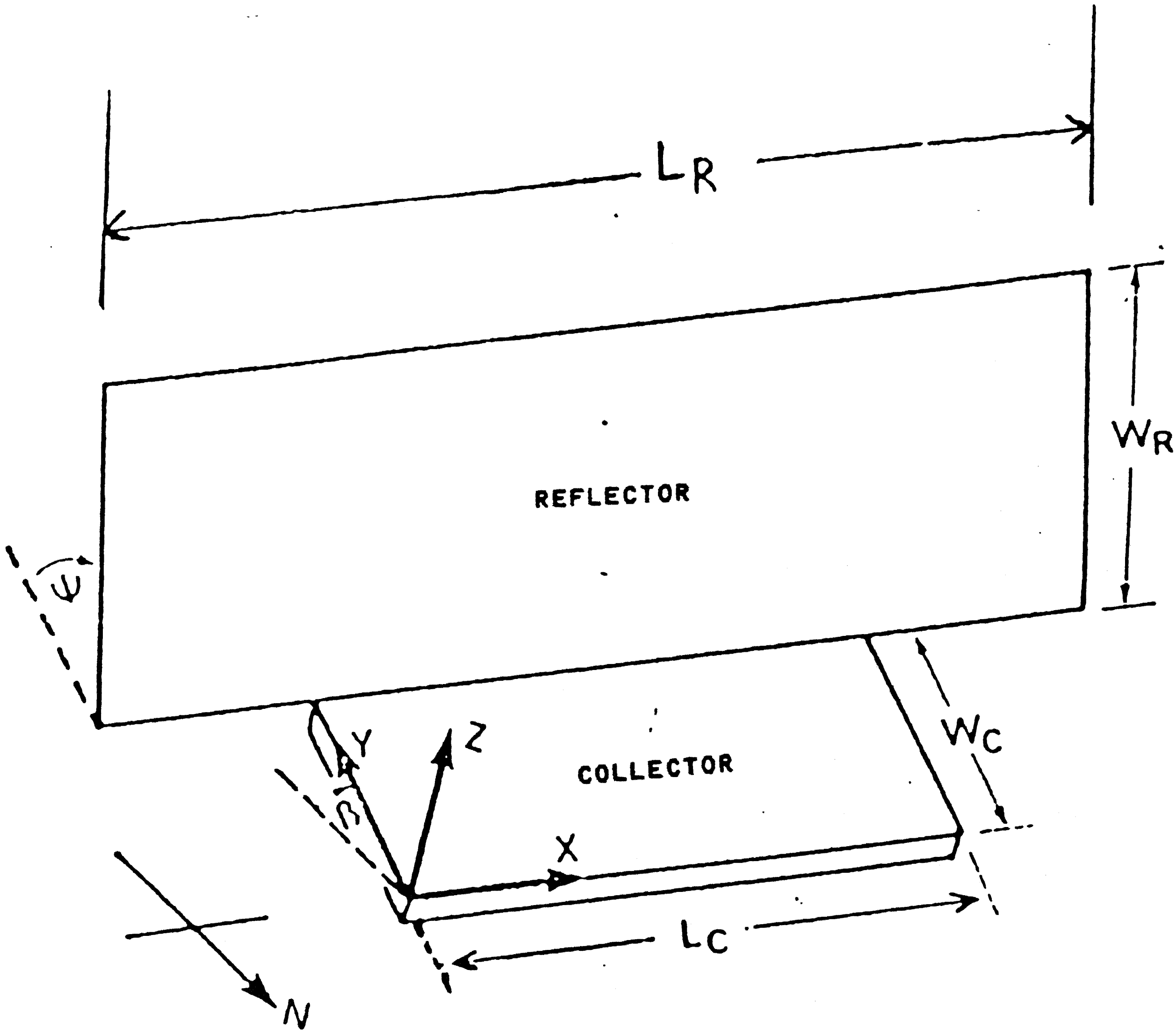


Fig. 1.2.2 Planar-reflector-collector geometry.

width, reflector angle relative to the plane of the cover and the angle through which the collector is tilted away from latitude inclination.

It is also found that the optimum reflector angle varies considerably, with the seasonal movement of the sun. As a consequence, a fixed reflector cannot provide reasonable year round flux augmentation.

b. Another model with a reflector below the collector combination used by Larson [6] for his experimental work is as shown in Fig. 1.2.3. Here the flat-plate collector and flat mirror were assumed to be of infinite length for the purpose of analysis. In the above model the reflector width is kept as twice the collector width. In the figure, γ represents the altitude angle of the direct beam radiation, ψ_p is the angle of tilt of the collector from the vertical and ψ_m is the angle of tilt of the mirror from the horizontal.

From the above experiment, Larson [6] found that the enhancement factor increases continuously with the increasing mirror width. However for an increase in mirror width more than twice the collector width, the enhancement factor increases very slowly. So the

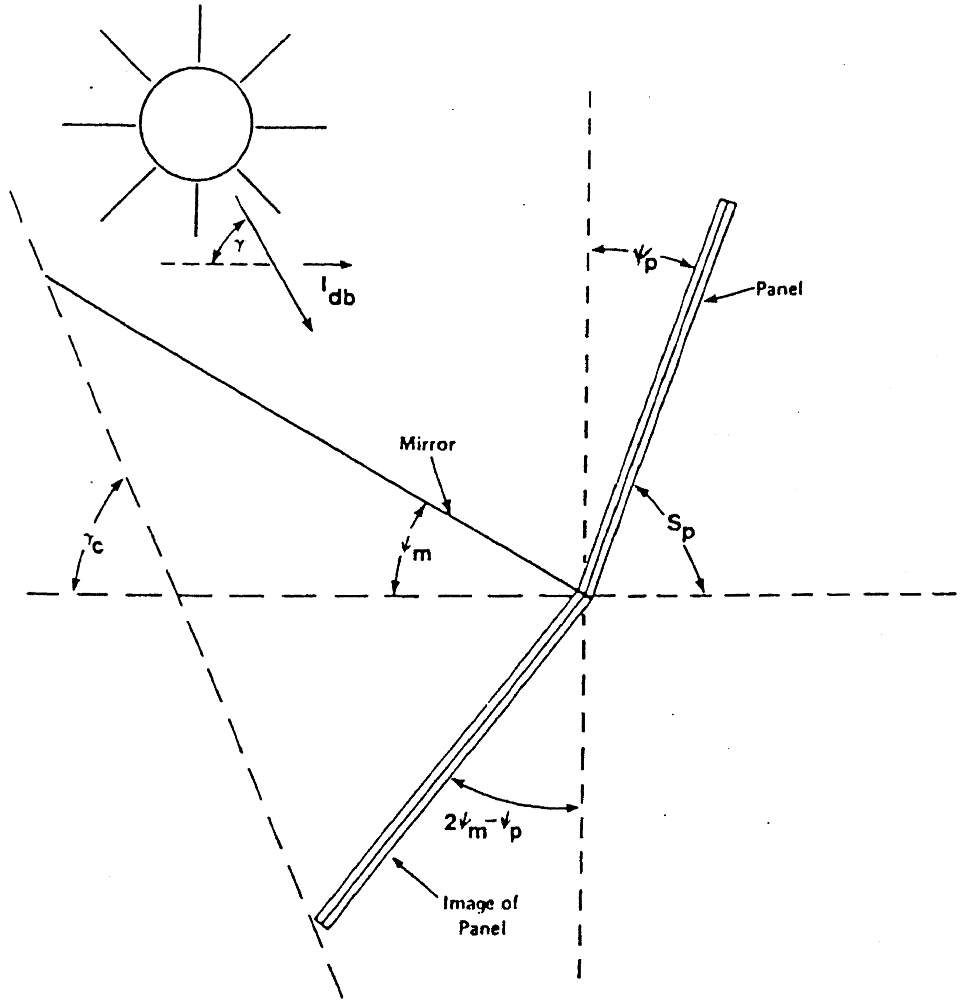


Fig. 1.2.3 Schematic of the flat-plate collector with the flat specular mirror placed below the collector.

practical mirror width appears to be in the range of one to two times the collector width. Larson also concluded that while using a planar-reflector-collector system the reflector orientation is more critical than the collector orientation. A change in the collector orientation away from the optimum value by $\pm$ 10 degrees reduces the enhancement factor by approximately 5 percent, where as a change in reflector orientation away from the optimal value by $\pm$ 10 degrees reduces the value of enhancement factor by approximately 14 percent.

c. Some others have tried to experiment by simultaneously mounting a top and a bottom reflector, arranged in a symmetrical trough configuration [7]. Fig. 1.2.4 shows such an arrangement. Yet others have tried by mounting four reflectors on all the four sides of the collector as shown in Fig. 1.2.5.

A trough configuration is found suitable only if a year round increase in performance is required. However if only winter or summer enhancement is required a single reflector-collector system is found to be ideal.

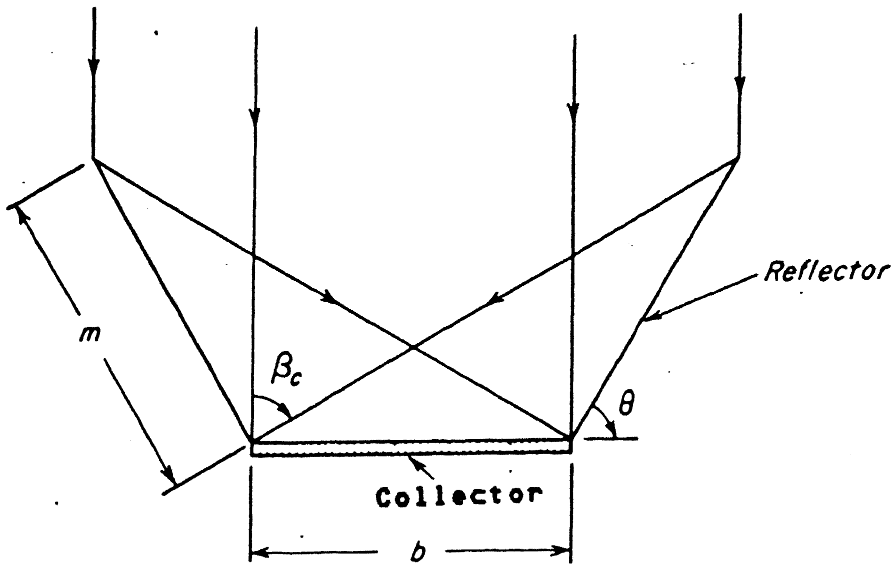


Fig. 1.2.4 Collector with two reflectors at top and bottom.

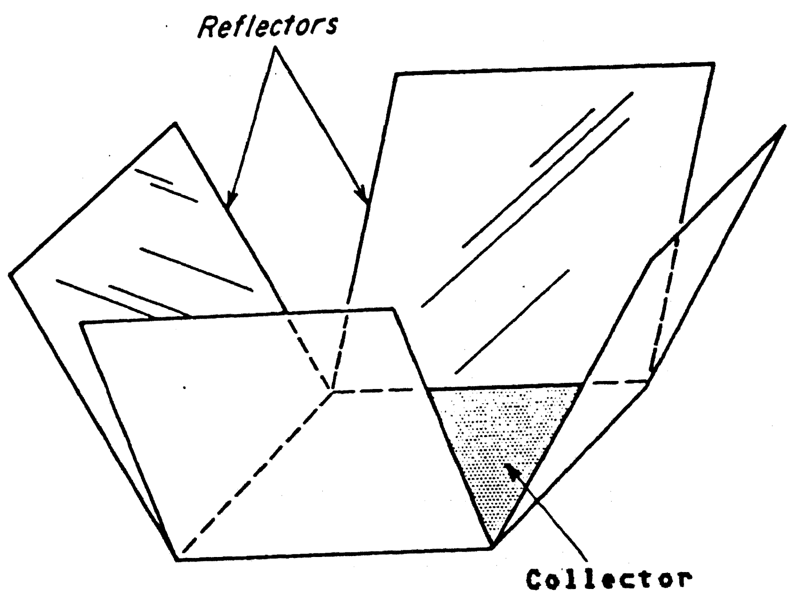


Fig. 1.2.5 Collector with reflectors mounted on all four

d. Espy [9] used a row of collectors fitted with planar reflectors. It is seen that approximately 50 percent cost is saved in the construction of the collectors for a desired output. This is because the cost of the reflector is low compared to the cost of construction of the collector.

e. Grimmer & Zinn [11] conducted experiments with several distinct types of reflective surfaces. The output of the collector is found to vary depending on the reflective properties of the surfaces. Result of the above experiment can be seen in Fig. 1.2.6. The figure shows the predicted total daily intensity plotted as a function of time of the year for various reflector-collector configurations. Curve A (dashed) is for a 55 degree tilted collector without reflector. Curve B is for a 90 degree tilted collector with a white paint reflector ($\rho = 0.80$). Curve C is for a 90 degree tilted collector with a silver paint reflector ($\rho = 0.73$). Curve D is for a 90 degree tilted collector with a silver paint reflector ($\rho = 0.52$). Curve E is for a 90 degree tilted collector with specular mirror reflector ($\rho = 0.80$). Curve F is for a 90 degree tilted collector without a reflector. Here the collector were single-glazed.

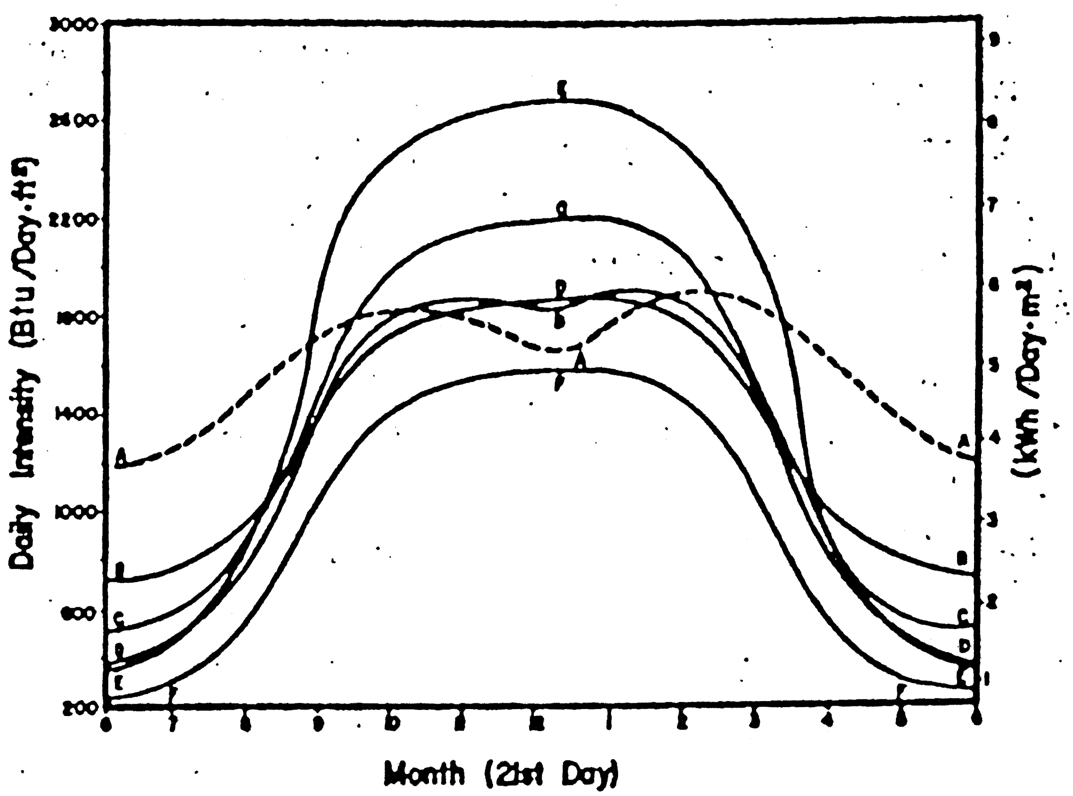


Fig. 1.2.6 Predicted total daily intensity for various collector-reflector configurations.

1.3 AIM OF THE PRESENT WORK

Whilst the results presented in literature are in general agreement that reflectors are beneficial, it is difficult to conclude the optimum configuration for a particular locality for a particular season.

If a planar-reflector-collector system is to be set up in any locality in India, suitable data should be available for its optimum configuration. The present work has been aimed at generating some data for Kanpur, 26°N latitude, during winter season.

Therefore the aim of the experiment has been to study the enhancement in the thermal energy output from a flat-plate water heater fitted with a single planar-reflector on top. By keeping the width to width and length to length ratio between the collector and reflector constant, the aim has also been to determine the maximum increase in thermal energy output and to establish the optimum tilt of the collector-reflector combination for the winter season.

1.4 RELEVANT GEOGRAPHICAL AND SOLAR DATA FOR KANPUR

Kanpur lies at 26° 28′ N latitude and 80° 21′ E longitude. Observed values of global radiation for Kanpur published by the India Metro logical Department are presented in Table 1.4.1 [10]. This table gives the monthly averages for total irradiation on horizontal surfaces, exposed to the sun on clear days, at Kanpur. These values match very well with values measured with a Pyranometer.

The sky (diffuse) radiation on a horizontal surface is estimated to be approximately 15% of the total radiation received on a clear day [10]. Therefore, direct or beam radiation is approximately 85% of the total radiation.

STATION KANPUR   PERIOD OF DATA NOVEMBER 1968 TO DECEMBER 1971

MONTH	HOURLY SUMS IN CAL/SQ.CM. FOR THE HOUR ENDING AT--													
	06	07	08	09	10	11	12	13	14	15	16	17	18	19
JANUARY		0.6	8.7	23.6	36.6	45.4	50.4	52.1	46.9	37.5	24.4	9.3	0.[illegible]	
FEBRUARY		2.0	14.8	31.3	44.9	56.1	52.2	61.5	55.1	44.9	30.9	14.0	1.[illegible]	
MARCH		4.8	21.2	39.8	53.4	62.7	59.8	69.2	63.6	54.4	39.1	21.8	5.6	0 2
APRIL	0.7	9.8	26.8	45.4	59.8	69.9	75.1	77.0	71.4	59.4	44.4	26.0	9.1	0 4
MAY	1.7	12.0	28.2	44.2	58.3	67.2	72.6	71.6	57.2	59.1	44.5	28.3	11.[illegible]	1 4
JUNE	1.9	9.8	22.9	36.5	44.7	55.1	55.8	63.1	56.7	47.7	36.6	24.1	10.9	1 [illegible]
JULY	1.4	9.2	21.8	36.4	45.6	56.7	59.8	55.3	54.6	45.9	37.5	24.7	10.7	1 5
AUGUST	0.6	8.0	19.8	30.9	39.4	47.2	47.8	47.5	47.0	44.0	32.8	21.9	7.5	0 5
SEPTEMBER	0.1	5.0	18.7	33.5	46.1	51.7	54.2	51.9	47.8	43.6	31.6	18.7	5.[illegible]	0 1
OCTOBER		2.9	16.8	34.1	49.2	59.4	53.5	62.0	59.0	47.5	33.0	17.1	3.[illegible]	
NOVEMBER		0.9	11.0	27.2	41.2	51.6	56.5	57.4	51.7	40.4	25.9	9.9	0.7	
DECEMBER		0.4	8.2	23.1	37.1	47.4	53.7	53.6	48.1	37.8	23.0	7.9	0.[illegible]	

Table 1.4.1: Monthly average for total, irradiation on a horizontal surface at Kanpur.

CHAPTER II

FLAT-PLATE COLLECTOR DESIGN AND EXPERIMENTAL SET-UP

2.1 FLAT PLATE COLLECTOR DESIGN AND CONSTRUCTION

The flat-plate collector is basically a black metallic surface that is placed at an appropriate angle to the daily motion of the sun, and provided with a transparent cover and appropriate insulation around the sides and the bottom. The heat transfer fluid is water. Fig. 2.1.1 shows the sketch of the flat plate collector, which was fabricated for this experiment. Fig. 2.1.2 shows the cross section of the flat plate collector showing its various components. For this experiment a square collector of 1 m x 1 m was fabricated, yielding a unit collector surface area (refer to plate 2.1.3).

Three of the principal types of absorber plate configurations are shown in Fig. 2.1.4. The most efficient configuration of a solar absorber plate is the integral flow tube pattern. Construction of this type of absorber involves fusing two sheets of metal in which the flow tube pattern has been coated with a resist. After fusing, the flow pattern is pneumatically inflated. This results in the flow tube being totally encapsulated between the two fused sheets of metal and a

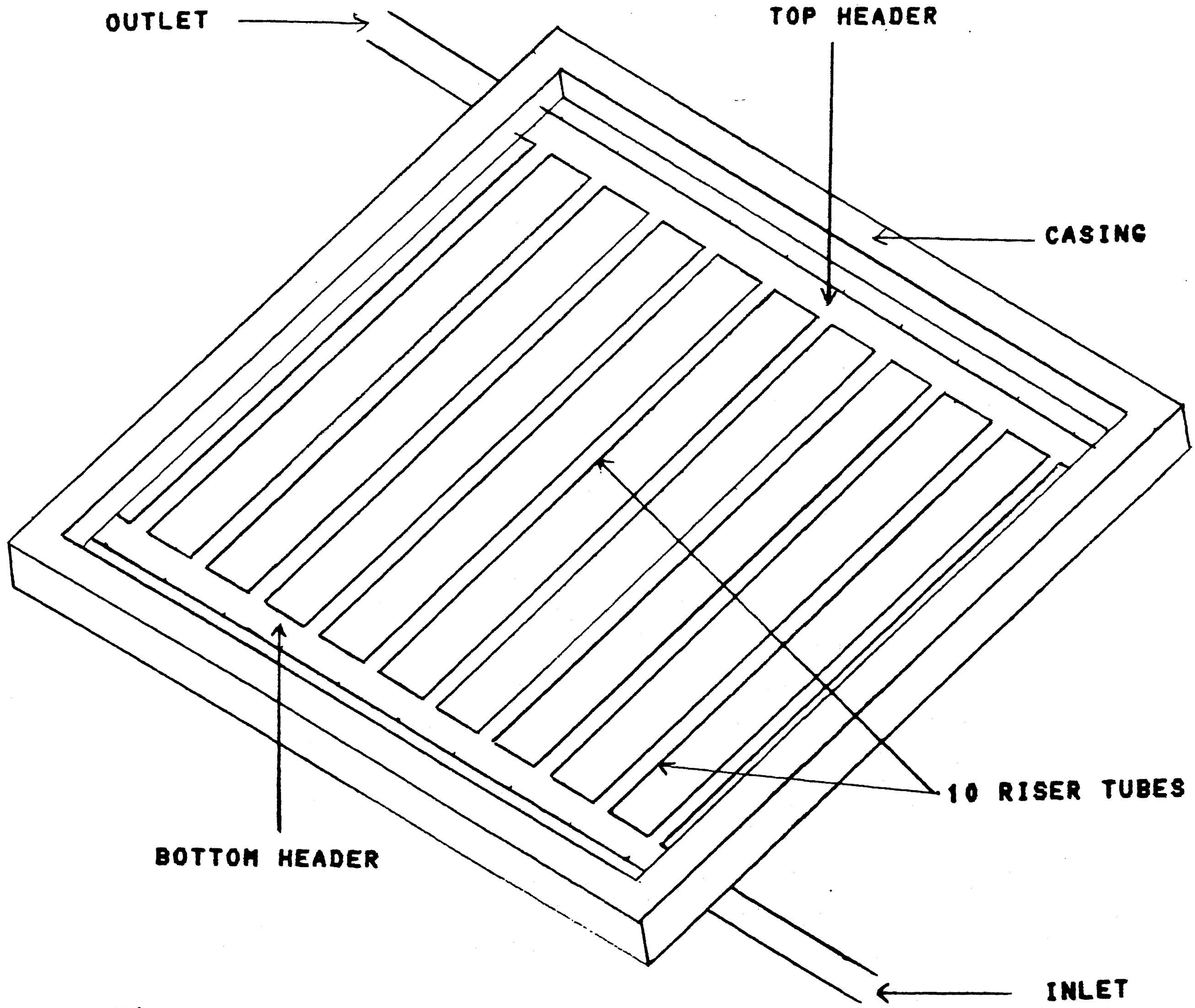
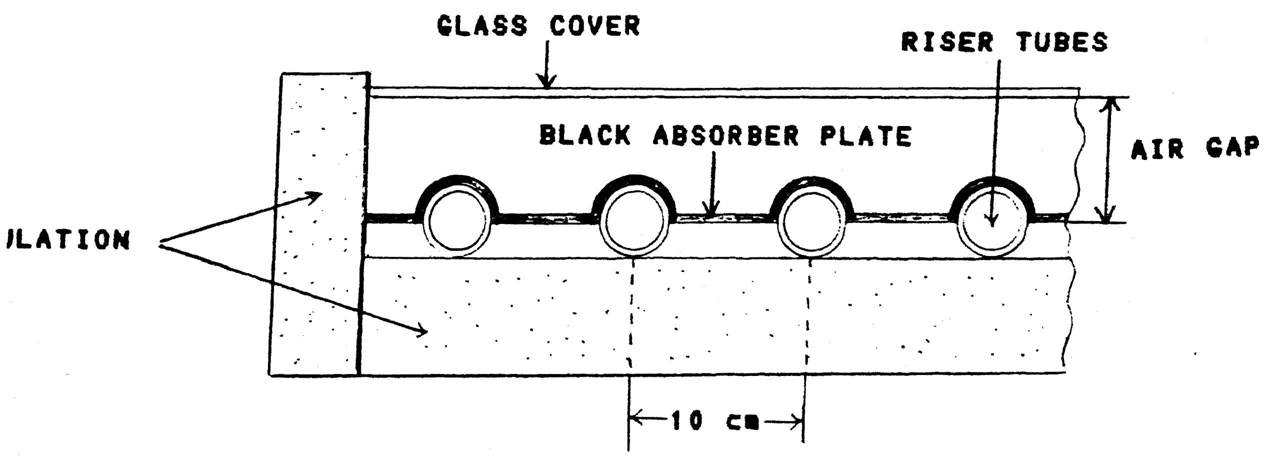


Fig. 2.1.1 Sketch of the Flat Plate Collector.



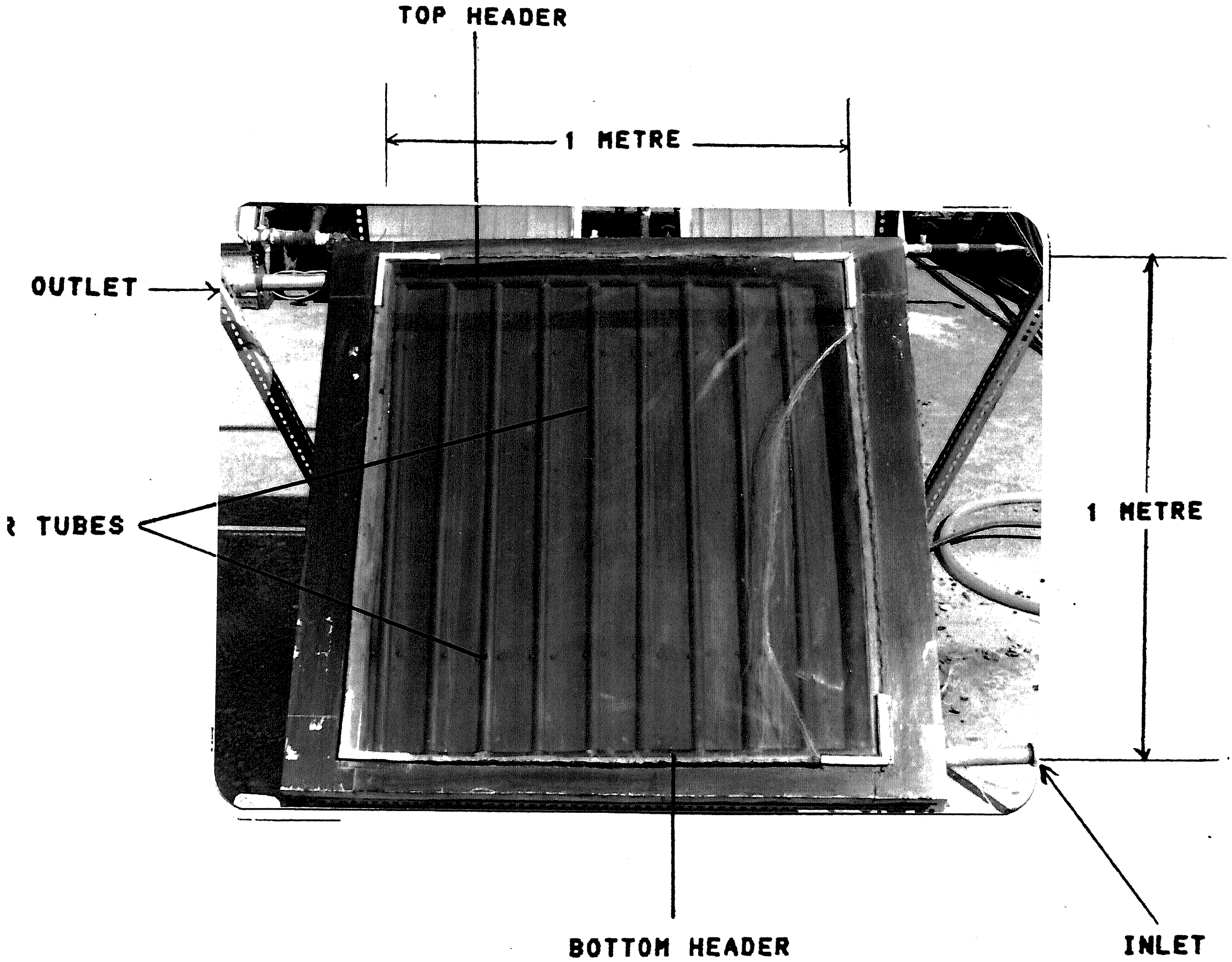


Plate 2.1.3 Photograph of the flat-plate collector.

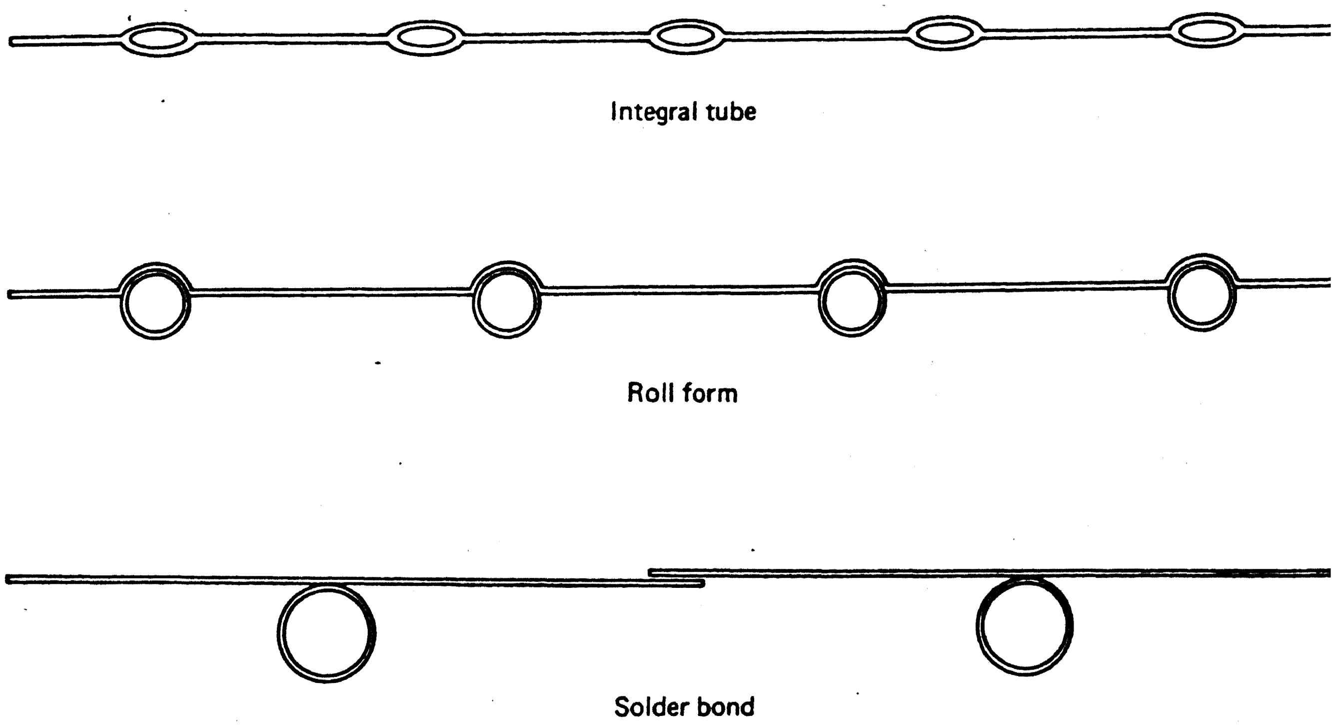


Fig. 2.1.4 Three principal types of absorber plate configurations.

high degree of contact between the surface area of the absorber and fluid flow channels within. Also, integral flow absorbers posses great strength and durability, as well as the ability to perform under a wide range of temperature extremes without being subject to significant deformation. Intricate flow patterns can be achieved with this type of design, resulting in very high operating efficiencies.

The roll-form type absorber, is the most commonly used and is in widespread production. This fabrication technique involves a sheet of metal that is rolled and clamped around the absorber riser tubes. The space between the absorber sheet and the riser tube is usually filled with a high temperature solder or similar heat conducting material. This results in efficient heat transfer from absorber plate to heat transfer fluid. The use of dissimilar metals for the absorber sheet and flow tubes should be avoided due to corrosion that would result from electrolytic decomposition at the junction of the two metals. In the present experiment the roll form type absorber was chosen because its fabrication is much simpler compared to the integral tube type.

The solder bond absorber configuration is the most easily constructed of all types of absorber plates. The major draw back in this type of absorber plate configuration is the relatively poor thermal contact between the absorber plate and

the flow tube passage, resulting in lower operating efficiencies than the other two configurations described.

When solar radiation passes through the transparent cover (glass) and impinges on the blackened absorber plate of high absorptivity, a large portion of this energy is absorbed by the plate and transferred to the water flowing through the tubes attached to the bottom side of the absorber plate. The absorber plate, a 22 gauge galvanized iron sheet painted black, has 10 semi-circular domes of 1/4" radius at a pitch distance of 10 cm each to fit the water carrying tubes snugly when placed over them yielding maximum semi-circular area of contact between the plate and the tubes. This is shown in Fig.2.1.2.

Lot of difficulties were faced during the fabrication of the absorber plate into the desired configuration. The 10 semi-circular domes, which house the water carrying tubes had to be made manually, since there is no machine available in our Solar Energy Laboratory for this purpose. Therefore, this process was time consuming, and could not be done to the desired accuracy.

The bottom of the absorber plate, the tubes and the sides are well insulated with glass wool to reduce conduction losses. The 1/2" water tubes are welded to the header at the top and the bottom. The water enters through the bottom header and goes out through the top header. The headers are galvanized iron tubes

of 1" dia. The mass flow rate is controlled through a valve at the entry to the bottom header.

The transparent glass cover is used to reduce convection losses from the absorber plate to the surroundings. It also reduces radiation losses from the collector because the spectral transmissivity of glass is such that it is transparent to short-wave radiation emitted by the sun, but nearly opaque to long wave thermal radiation emitted by the collector. In solar energy applications when flat plate collectors are used, the collector is tilted, so that it is roughly normal to the sun's rays, when maximum energy collection is desired. The collector is oriented directly towards the equator, facing south. For the year round application without tracking the optimum tilt angle of the collector is equal to the latitude angle of the location. For winter application only, the tilt angle should be 15° more than the latitude.

2.2 PLANAR REFLECTOR DESIGN AND MOUNTING

A plane reflector is mounted on top of the collector with the help of hinges. Apart from the hinges at the bottom of the mirror, two slotted angle iron side supports are provided which help not only to hold the mirror at any desired angle but also to lock it. Additional holes are drilled along the slotted angle iron frame of the reflector (as can be seen from the

photograph) and for any desired tilt angle , a hole on the reflector frame and a hole on the side support are made to coincide and the reflector locked into position by inserting a pin through both the holes (refer to Plate 2.2.1). This provision is there on either side of the reflector. The reflector is 2 m long and 1 m wide. The width of reflector is equal to the width of the collector and an overhang of half the width of the reflector is given on either side of the collector making the total length of the mirror equal to double the length of the collector. This geometric ratio between the collector and reflector lengths is found to be optimum for maximum thermal energy output [7]. Increasing the length of the mirror beyond this does not add appreciably to the enhancement of thermal energy output by the collector but causes problems in mounting and manipulating the reflector. The reflector frame is made of plywood and wooden strips.

2.3 EXPERIMENTAL SET-UP

The set-up of the experiment is shown in Plate 2.3.1. and Fig. 2.3.2. In the figure S_c and S_r represents the tilt angle of the collector and reflector, respectively with respect to the x-axis or the horizontal plane. The collector is tilted towards the equator (south) and kept at an angle of 41° (latitude + 15°) for optimum winter solar energy collection. The collector is 1 meter long and 1 meter wide. Above the collector the

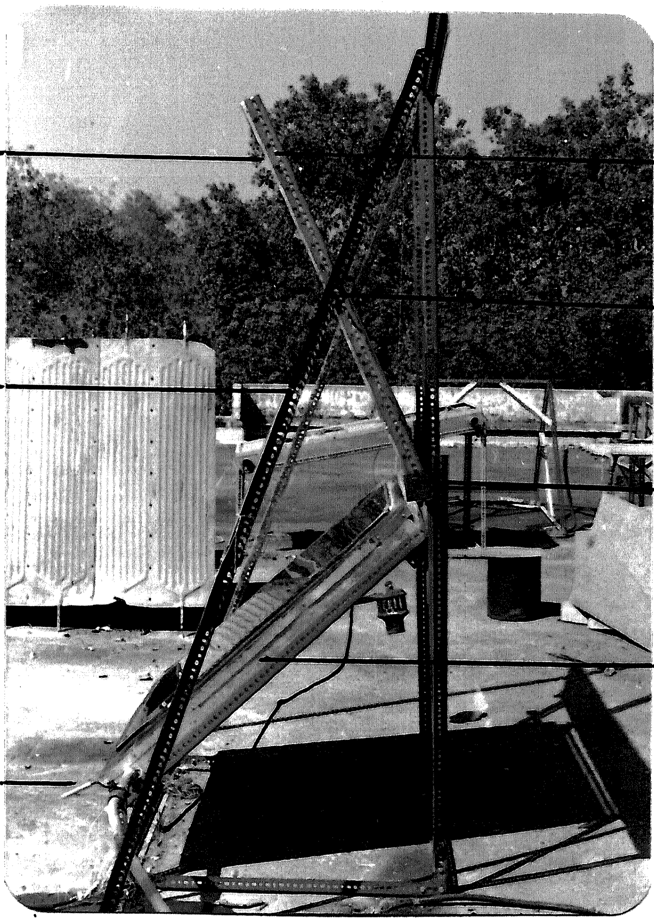


Plate 2.2.1 Photograph showing the side view of the experimental test rig.

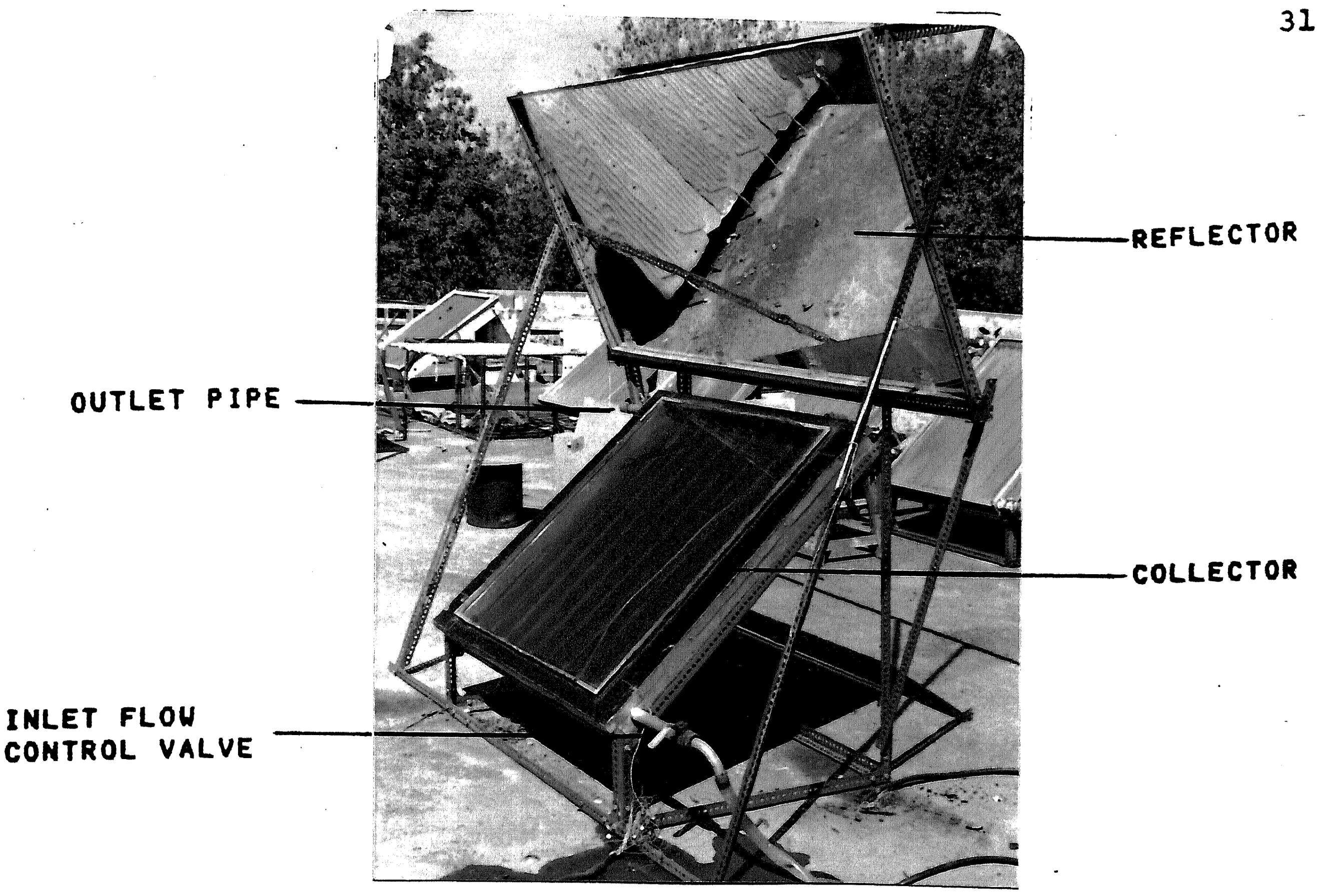


Plate 2.3.1 Photograph showing isometric view of the experimental test rig.

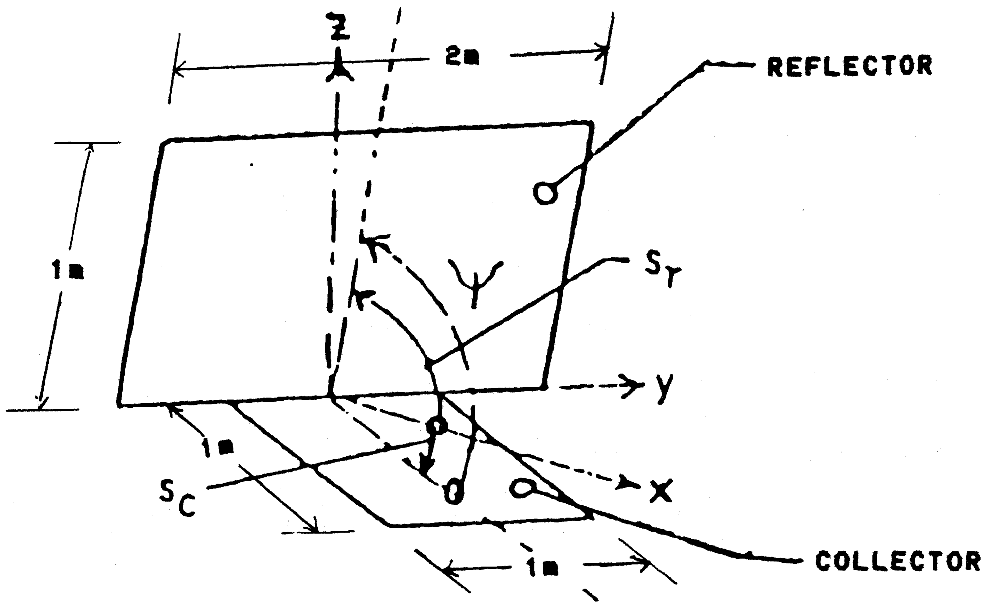


Fig. 2.3.2 The planar-reflector-collector system showing the reflector and the collector tilt angles.

planar reflector of 2 m length and 1 m width is mounted on hinges, and held by side supports so that the mirror can be tilted on its hinges and kept at any desired angle with the help of the side supports. This arrangement is very versatile and is suitable for the year round optimum collection because the collector and the reflector tilt can be changed manually and can be set at an optimum angle for a particular season. The entire rig is supported by a slotted angle iron frame. The water connection is taken from the main water supply line with the help of a pipe and the inlet is provided through the bottom header.

2.4 TEST PROCEDURE

The object of the investigation is to compare the performance of a collector-reflector system with a plane collector without the reflector under identical operating conditions, for the latitude of Kanpur, during winter season.

The collector-reflector system is mounted on an angle iron frame. The water supply to the collector is made through a polythene pipe connected to the water main. The mass flow rate of the water is controlled through a valve fitted to the collector at its inlet. The mass flow rate is maintained approximately at 0.01 kg/s, so that an appreciable temperature difference is obtained between the inlet and the outlet water.

Mass flow rate can be measured at any time during a test run by direct measurement of the volume discharged, with the help of a calibrated flask and a stop watch. This mass flow rate also has the advantage of removing through the pipes, any air released by the water during heating because although the flow is continuous the tubes are not running full of water.

The readings are taken by keeping the reflector at various angles. Thermometer is used to measure the ambient, the inlet and the outlet water temperatures. The collector inclination through out the experiment is kept constant i.e. at optimum winter tilt of 41°, equal to (latitude + 15°) = $26^\circ + 15^\circ$, for Kanpur. Readings are also taken for the collector alone, by removing the reflector.

Readings have been taken for the months of December, January and February, but only the readings taken on clear successive sunny days have been considered. The results are presented in the form of graphs from Fig. 3.3.1 through to Fig. 3.3.3.

CHAPTER III

RESULTS AND DISCUSSION

3.1 ENERGY COLLECTION

Rate at which useful energy is collected by flat plate collectors can be written as:

$$Q_u = A_c F_R [q_A - U_L (t_{in} - t_{amb})]$$

Where Q_u is the rate of useful energy collection in Watts, A_c is the area of the collector in m^2, F_R is the plate efficiency factor, q_A is the rate of energy absorbed per unit area in W/m^2 & U_L is the collector loss coefficient in W/m^2 K. Values of F_R and U_L, dependent on collector parameters and the weather, can be calculated [5].

For the collector with no reflector, the rate of energy absorption per unit area q_A can be calculated by

$$q_A = (\tau\alpha)_{bc} I_{bc} + (\tau\alpha)_{dc} I_{dc}$$

where the incident radiation I is considered to have beam and diffuse components, I_{bc} and I_{dc} respectively, and the transmittance-absorptance product $(\tau\alpha)$ is a modified form of $\tau\alpha$ which allows for the inter-reflection between the absorbing

plate and the cover system. $(\tau\alpha)$ is dependent on the angle of incidence , and is calculated in the case of diffuse radiation as though the angle of incidence is the same as for the beam radiation on clear days.

It is assumed that the presence of the reflector does not alter the diffuse radiation falling on the collector from the sky, so that

$$q_A = (\tau\alpha)_{bc} I_{bc} + (\tau\alpha)_{dc} I_{dc} + (\tau\alpha)_{rc} \rho_r I_{br} \frac{A_{rc}}{A_c}$$

where the exchange area A_{rc} equals A_r f_{rc} and represents an effective area for radiative interchange between the reflector and collector surfaces. In the above equations the subscripts b, d, and r stand for beam, diffuse and reflector, respectively. In the case of a collector with a specular reflector the reflected beam component normal to the collector is ρ_r I_b cos θ_{rc}, where θ_{rc} is the angle of incidence on the collector of the reflected beam. At certain times the reflected beam may not cover the total area of the collector, so a factor f_{rc} is used. $(\tau\alpha)_{rc}$ calculated at the incidence angle θ_{rc} is applied as before.

$$q_A = (\tau\alpha)_{bc} I_{bc} + (\tau\alpha)_{dc} I_{dc} + (\tau\alpha)_{rc} \rho_r f_{rc} I_b \cos \theta_{rc}$$

The actual value of q_A may be less than that indicated above due to dust (D), shading of the absorber plate by the

collector walls (S), and shading by the reflector(S_{rc}). These effects can be allowed for by reducing q_A by the fractions, D, S, and S_{rc}, respectively.

$$q'_A = q_A (1 - D) (1 - S) (1 - S_{rc})$$

In the experiments the collector has been kept reasonably clean so that D was taken as 0.01. The shading factor S was assumed to vary sinusoidally with a period equal to the day length, a maximum value of 0.1 at sunrise and sunset and a minimum value of zero at solar noon.

3.2 COLLECTOR AREA EXPOSED TO SPECULAR RADIATION

The fraction of the collector area exposed to reflected radiation ρ_{rc} depends on the system geometry and position of the sun. For a collector-specular reflector system as shown in Fig. 3.2.1, the area receiving reflected light can be found from a knowledge of the point A', at which the reflected ray from the top corner of the reflector A is incident in the plane of the collector [5]. The required area A'FKLE can be completed since A'E is parallel to AB and A'FC is a straight line. The fraction f_{rc} is given by the ratio of the area exposed to reflected radiation i.e. area A'FKLE, in the case shown, to the collector area.

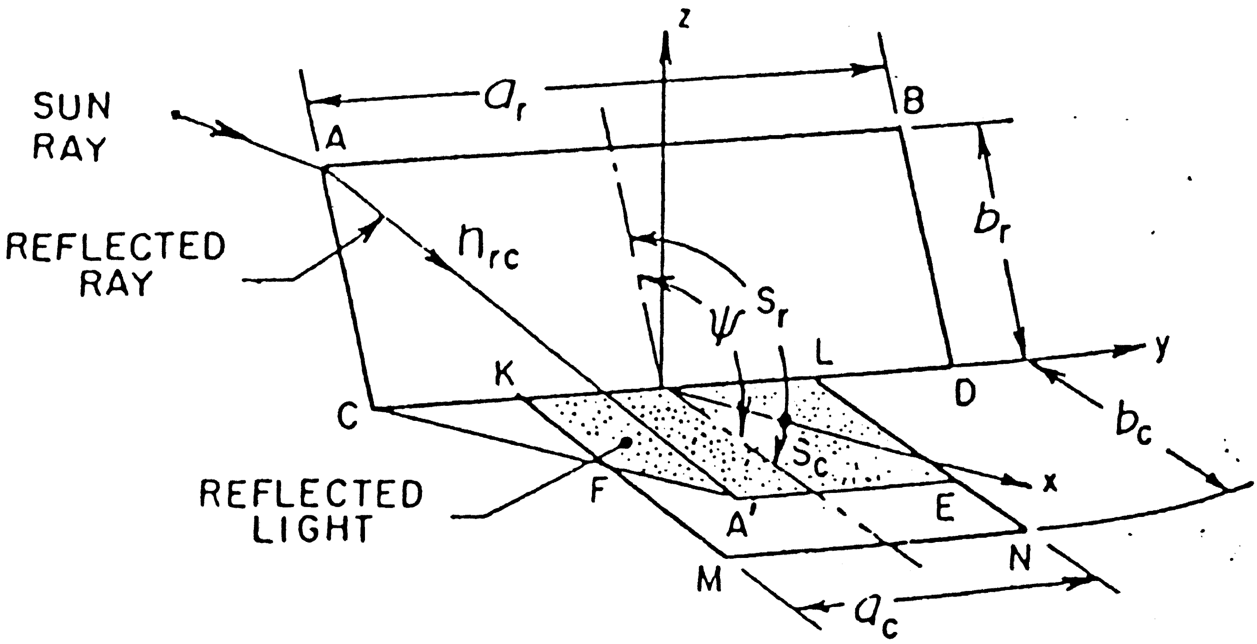


Fig. 3.2.1 Collector - Specular reflector system.

For the morning hours (hour angle ω being +ve) the situation is described by Fig. 3.2.1 but in the afternoon (ω being - ve), point B will be applicable instead of point A. However, the same method will cover both situations.

Any point p in the plane of the collector can be specified by its position vector p,

$$p = xi + yj + x \tan s_c \, k$$

where i,j and K are unit vectors in the co-ordinate directions x, y, z.

The position vector a′ of point A′ can be found from [5]

$$a' = a + C \, n_{rc}$$

where $a = b_r \cos s_r \, i - a_r/2 \; j + b_r \sin s_r \, k$

and $n_{rc} = ui + vj + wk,$

a unit vector directed from the reflector towards the collector. In the above equations S_c and S_r denote the angle of tilt of the collector and the reflector, respectively, with respect to the horizontal (See Fig. 3.2.1.) The parameter C can be expressed in terms of u and w by solving the above equation,

$$C = \frac{b_r(\cos s_r \tan s_c - \sin s_r)}{w - u \tan s_c}$$

Hence

$$a' = (b_r \cos s_r\ Cu)i + (-\frac{a_r}{2}\ Cv)j + (b_r \sin s_r + Cw)\mathbf{k}$$

From solar geometry, a unit vector in the direction of the solar beam can be expressed in terms of the solar altitude α and the hour angle ω by

$$n_b = -\cos\alpha\cos\omega i + \cos\alpha\sin\omega j - \sin\alpha\mathbf{k}$$

Hence for the particular case in which n_{rc} is a unit vector in the direction of a ray reflected specularly from the planar reflector, u, v and w can be calculated in terms of α and ω since

$$n_b \cdot n_r = - n_{rc} \cdot n_r$$

and

$$n_b \times n_r = n_{rc} \times n_r$$

where n_r is a unit vector normal to reflector.

3.3 RESULTS

The thermal energy output of the collector is recorded for various experimental runs of the system with the reflector held at various angles of tilt with respect to the horizontal plane. Table 3.3.1 shows the typical data recorded from each of these test runs.

DATE	SOLAR TIME	COLLECTOR ANGLE FROM HORIZONTAL	REFLECTOR ANGLE FROM HORIZONTAL	$\dot{m}$ (kg/s)	T_{in} (^{o}C)	T_{out} (^{o}C)	Output power $\dot{m}\, C_p(T_{out}-T_{in})$ (Watts)
16 Feb. 94	SOLAR NOON	41	70	0.016	27	40	869.4
17 Feb. 94	SOLAR NOON	41	75	0.016	27	41	975.3
18 Feb. 94	SOLAR NOON	41	80	0.0185	27	39.8	990.8
19 Feb. 94	SOLAR NOON	41	85	0.0116	27	46	921.2
20 Feb. 94	SOLAR NOON	41	90	0.016	27	40	869.4
21 Feb. 94	SOLAR NOON	41	WITHOUT REFLECTOR	0.0125	27	41	731.5
22 Feb. 94	1000 HRS	41	80	0.016	27	38	735.68
22 Feb. 94	1100 HRS	41	80	0.016	27	40.5	902.8
22 Feb. 94	1200 HRS	41	80	0.016	27	42	1003.2
22 Feb. 94	1300 HRS	41	80	0.016	27	41	936.32
22 Feb. 94	1400 HRS	41	80	0.016	27	38.5	769.1
23 Feb. 94	1000 HRS	41	WITHOUT REFLECTOR	0.0125	27	40	679.25
23 Feb. 94	1100 HRS	41	"	0.0125	27	40.8	721.05
23 Feb. 94	1200 HRS	41	"	0.0125	27	41.5	757.6
23 Feb. 94	1300 HRS	41	"	0.0125	27	41	731.5
23 Feb. 94	1400 HRS	41	"	0.0125	27	40.2	689.7
24 Feb. 94	SOLAR NOON	31	80	0.016	27	41	940

Table 3.3.1: Experimental results in a tabular form.

For comparing the thermal energy output at various reflector tilt angles, the test values are plotted graphically with the X-axis giving the reflector tilt angles from the horizontal in degrees, and the Y-axis representing the instantaneous thermal energy output measured at solar noon in Watts. Fig. 3.3.1 exhibits the best fitting curve drawn through the resulting points. (Refer to Appendix A for the general equation of the curve).

From Fig. 3.3.1 the optimum angle of tilt of the reflector can be determined as the angle corresponding to the maximum thermal energy output of the collector i.e., the peak of the curve. Therefore for winter season, in Kanpur, the optimum tilt angle of the reflector is observed to be approximately 80° from the horizontal.

After finding the optimum angle of tilt of the reflector, at which the thermal energy output from the collector is a maximum, readings were recorded over a clear sunny day to compare the performance of the collector-reflector system with that of a simple collector alone. These data are also tabulated in Table 3.3.1. Fig. 3.3.2 gives the variation of thermal energy output with the time of the day. During the above test runs the reflector is held at the optimum tilt angle of 80° to the horizontal while the collector is kept at a tilt of 41° to the horizontal.

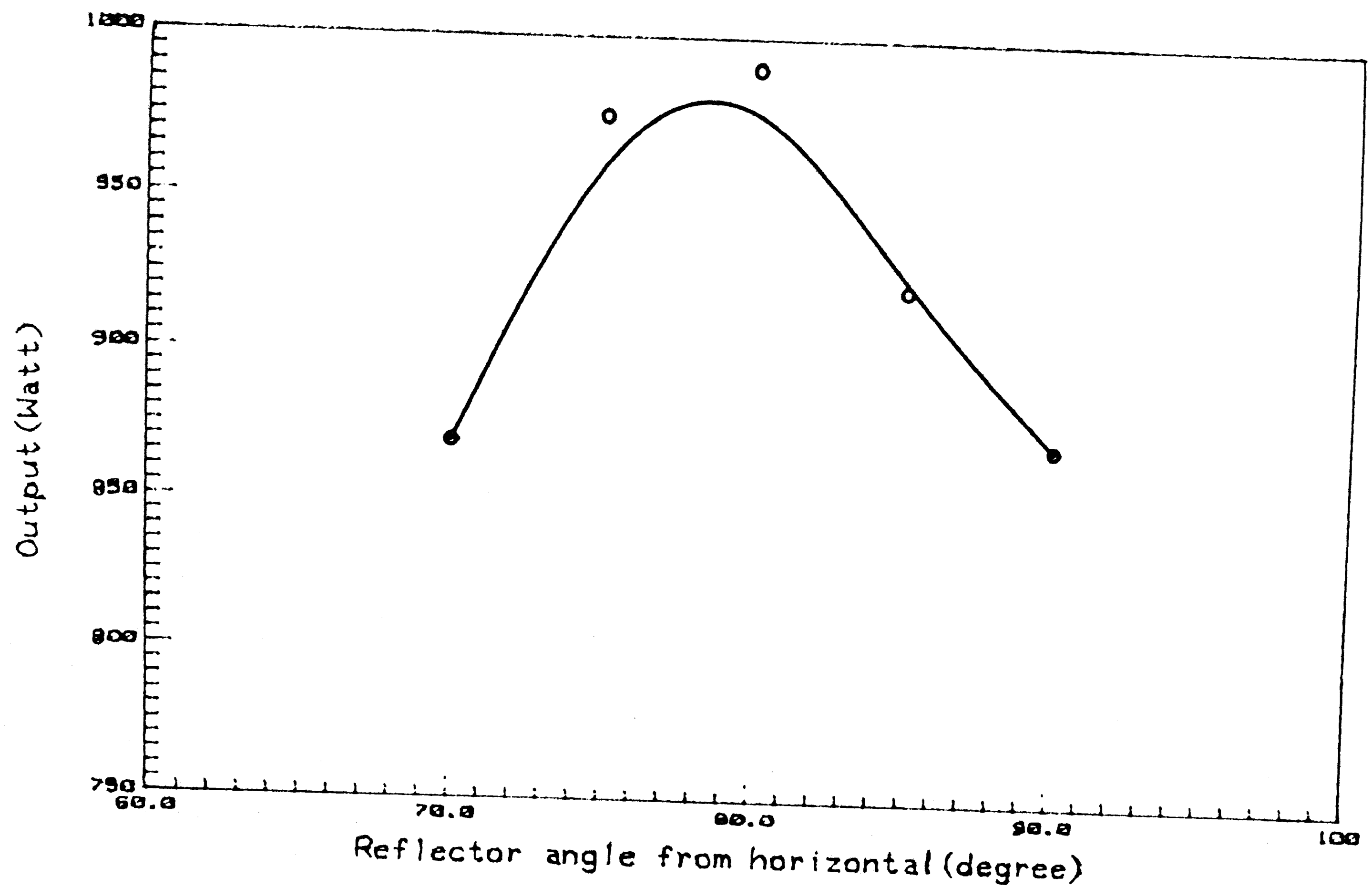


Fig. 3.3.1 Instantaneous output at solar noon at various reflector angles.

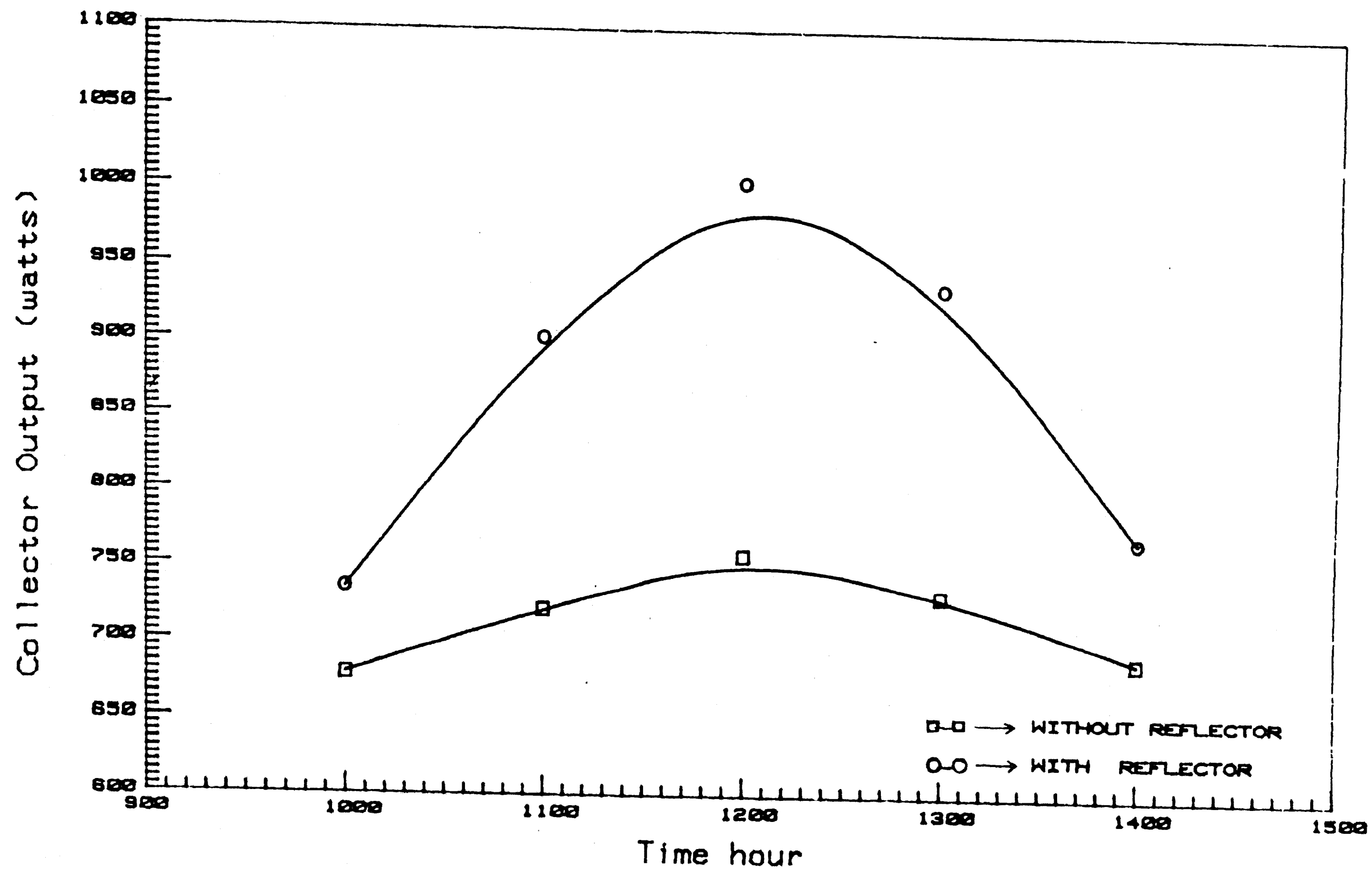


Fig. 3.3.2 Performance curve of specular reflector-collector system and that of the collector alone over a day.

It can be seen that at solar-noon the increase in instantaneous thermal energy output with collector-reflector combination is about 35% higher compared to a simple flat-plate collector. However the average daily output would show an increase of only 23%, since the increase in thermal energy output is low in the morning and evening hours compared to solar noon. Fig. 3.3.3 shows the percentage increase in thermal energy output , with the time of the day.

These above values of thermal energy output are comparable to the values found in literature. Grassie and Sheridan [5], during an experiment conducted in Australia obtained an increase in instantaneous thermal output of 24% with the help of a reflector above a collector compared to a simple flat-plate collector with no reflector at all. The average thermal energy output over a full day showed an approximate increase of only 14%.

Therefore, it is seen that, for water heating applications in winter, planar-reflector combination serves as an inexpensive means of augmenting the thermal energy output of a flat-plate collector. However it is essential to obtain the data for the optimum tilt angle of the planar-reflector-collector system, at a particular location.

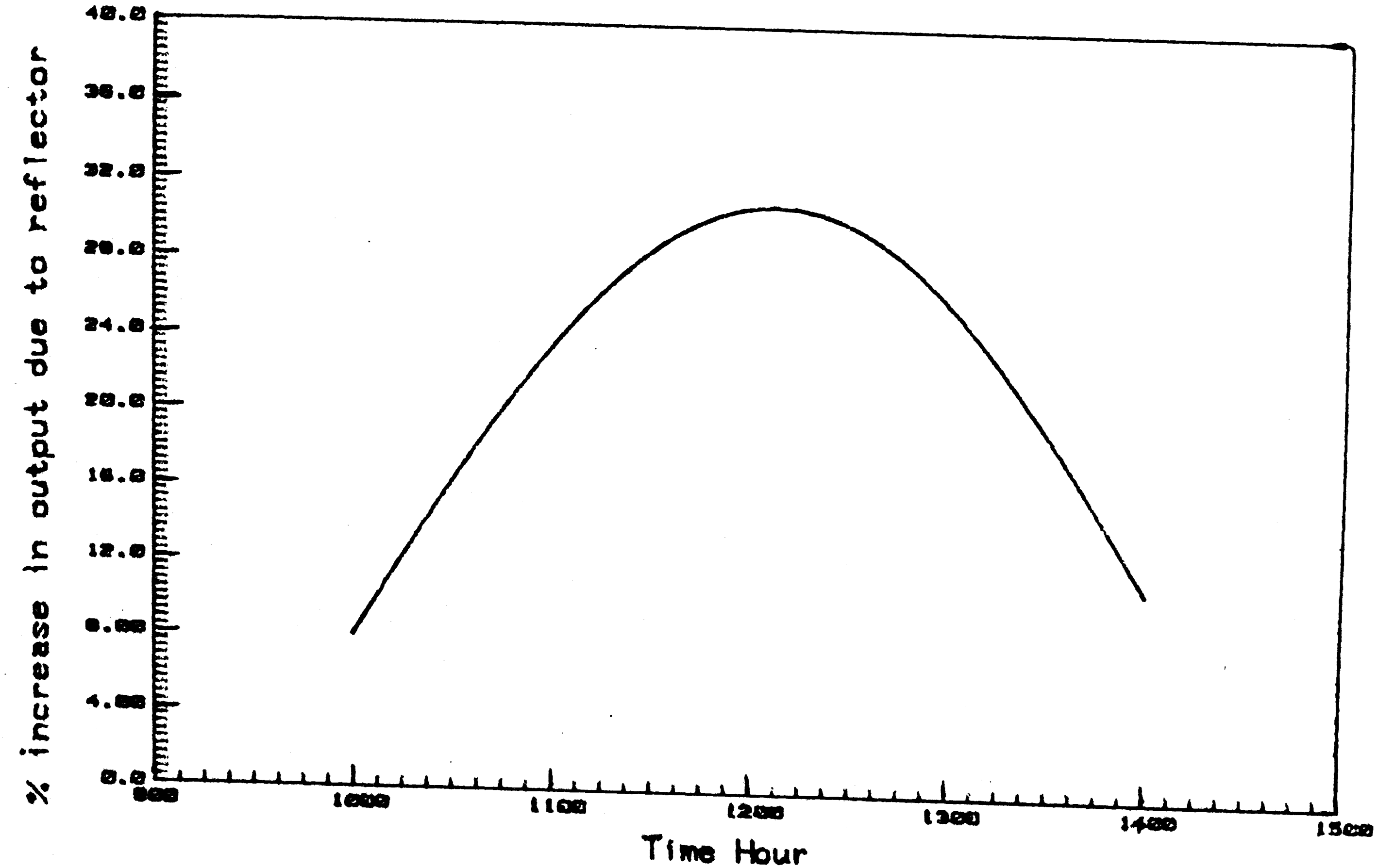


Fig. 3.3.3 Percentage increase in thermal energy output due to the reflector.

CHAPTER IV

CONCLUSIONS AND SUGGESTIONS

4.1 CONCLUSIONS

a. It was seen that a reflector located above the collector in a near vertical position, with respect to the horizontal plane through the hinges of the reflector, would be appropriate for water heating systems during winter at Kanpur, when the collector is tilted towards the South at an angle of 41° i.e. latitude + 15° to the horizontal for optimum winter collection.

b. Specular reflectors significantly enhance the performance of simple flat-plate collectors. The cost effectiveness of the system depends on the relative costs of the collector and the reflector surfaces. An augmentation factor of upto 1.35 has been achieved in the present investigation.

c. Reflector-collector systems should be designed keeping in view the desired load and the local weather data particularly, the cloudiness. However, the data presented in the thesis is for clear days only.

d. The commonly used prescriptions for orienting the flat-plate solar collectors is that the panels should be tilted from the horizontal by the latitude angle ϕ for the year-round collection and by $\phi \pm 15$ degrees for the optimum winter or summer collections, respectively. This prescription is somewhat over-simplified in that it ignores the seasonal variations in the available sunshine and changes in collector heat loss with the tilt angle. Considerable improvement in the performance is obtained by, determining the optimal orientations and the seasonal tilting strategies of the collector and the mirror for a variety of solar energy applications.

While augmenting the collector with a planar-reflector, the reflector orientation is more critical than the panel orientation. This is seen from Table 3.3.1. When the reflector tilt is increased from 70 to 80 degrees with respect to the horizontal, there is an increase in thermal energy output of the collector, by approximately 13 percent; whereas when the collector tilt is changed from 31° to 41° with respect to the horizontal the output energy increases by only 6 percent.

4.2 SUGGESTIONS FOR FUTURE WORK

a. The planar reflector-collector design presented in this thesis can be used to predict performance with other parameters and weather conditions. Based on monthly average values of radiation and temperature, an estimate of performance throughout the year can be obtained. Ideally for such an experiment data should be collected over a complete year.

Such an annual estimate was made for Brisbane (Australia) [5] with a collector inclined at - 35 °, reflector inclination of 70, 80 and 90°and inlet water temperature of 50 °C. Fig.4.2.1 presents the results of the investigation. Curves have been plotted for a collector with unit surface area.However, the extrapolation of outputs to larger collector areas will only be approximately correct as the proportion of edge losses will vary and the effect of the overhang will be different for other than square collectors. The advantage of the collector reflector system in meeting the hot-water load throughout the year is demonstrated by the load curve of Fig. 4.2.1. It is seen that the best way to meet this load is to use a 70 ° reflector and to move it to approximately 90° from September to March. The increase of output due to reflectors has also been expressed on a percentage basis in Fig. 4.2.2.

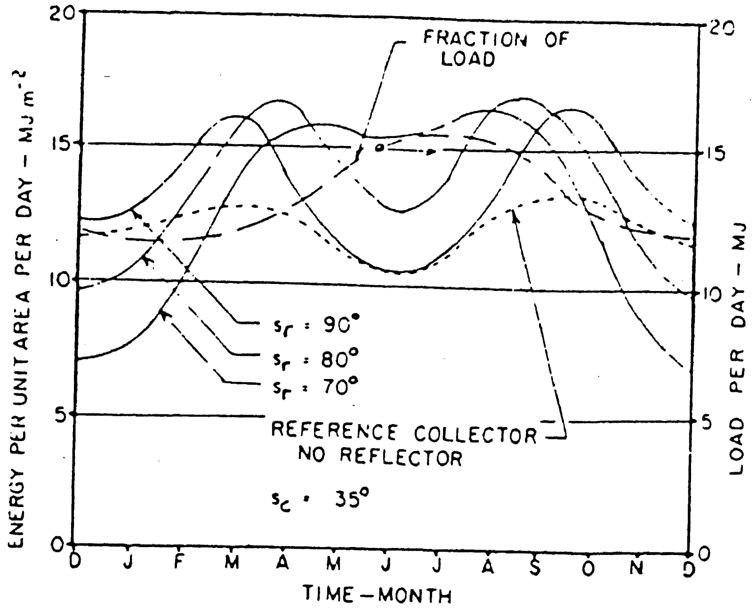
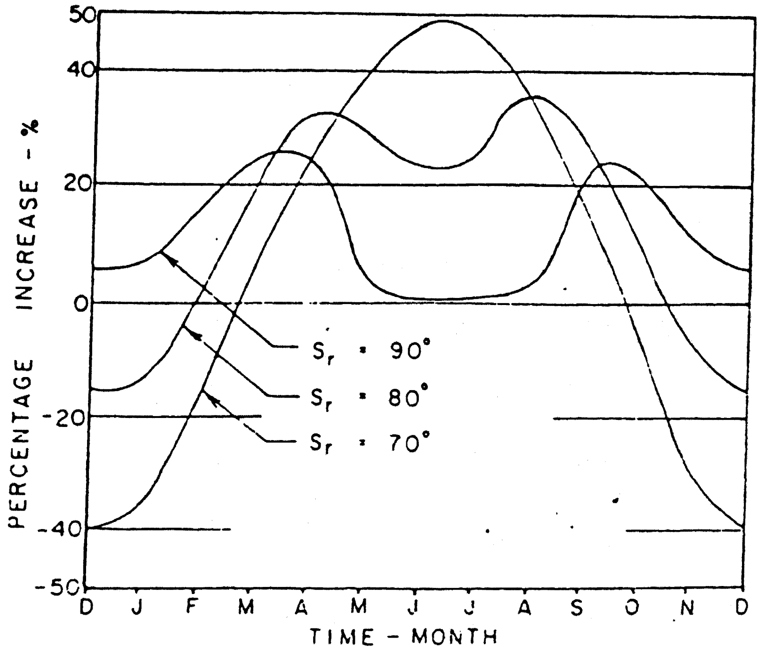


Fig. 4.2.1 Round the year performance of collector-reflector system.



g. 4.2.2 Percentage increase in thermal energy due to reflector above the collector

b. For community heating etc., an array of flat plate collectors could be considered, augmenting it with planar reflectors. Thus the reduction in the overall cost of construction could be estimated for a given thermal energy output.

c. Experiments could be done with several distinct types of selective reflector surfaces. The output of the collector would differ depending on the reflective properties of the surface.

d. With reference to conclusion (e), it is, desirable that the sizes of the collector-reflector combinations be standardized and various tilting strategies evolved for the year round optimal use of the combinations at various locations of the country. Data could be made available in the form of graphs or tables. This would help the users to a great extent.

e. Even though a top reflector is suitable for winter enhancement of thermal energy output, experiments could be conducted with top and bottom reflectors, both separately and collectively, to ascertain their efficacy for a year-round solar energy collection.

NOMENCLATURE

A	area, m^2
C	conductance, $W\ m^{-2}\ {}^\circ C^{-1}$
D	dust factor
F_R	plate efficiency factor
f	exposure factor
I	intensity of radiation, $W\ m^{-2}$
Q_u	rate of useful energy collection, W
q_A	rate of energy absorbed per unit area, $W\ m^{-2}$
S	shading factor
s	inclination of surface from horizontal (x-axis)
t	temperature, $^\circ C$
U_L	collector loss coefficient, $W\ m^{-2}\ {}^\circ C^{-1}$
α	solar altitude angle
ε	emissivity
θ	angle of incidence
ρ	reflectance
$(\tau\alpha)$	effective transmittance - absorptance product
ψ	angle between planes of collector and reflector
w	solar hour angle
i,j,k,n	unit vectors

SUBSCRIPTS

amb	ambient
b	beam
c	collector
d	diffuse
in	inlet
r	reflector
s	specular

REFERENCES

1. B.S. Magal, Solar Power Engineering, Tata McGraw-Hill Publishing Company Limited, 1990.
2. M.P. Agarwal, Solar Energy, S.Chand & Company Limited, 1985.
3. A.B. Meinal and M.P. Meinal, Applied Solar Energy-An Introduction, Addison-Wesley Publishing Co., 1976.
4. Jui Sheng Hsieh, Solar Energy Engineering, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1986.
5. S.L. Grassie and N.R. Sheridan - The use of planar reflectors for increasing the Energy yield of flat plate collectors, Solar Energy, Vol. 19, 663-668, 1977.
6. D.C. Larson - Optimization of Flat Plate Collector - Flat mirror system, Solar Energy, Vol. 24., 203-207, 1980.
7. H.F. Chiam - Planar concentrators for Flat-plate solar collectors, Solar Energy, Vol. 26., 503-509, 1981.
8. H.F. Chaim - Stationary reflector-Augmented Flat-plate collectors, Solar Energy, Vol. 29., 65-69, 1982.
9. P.N. Espy, Solar thermal collectors using planar reflectors, Proc. Int. Solar Energy Cong. 1977, New Delhi, India.

10. Capt. G.S. Gharjakia, Design, Fabrication and Testing of Stationary Solar concentrator, Master of Technology Thesis, Department of Mechanical Engineering, IIT Kanpur, August 1976.

11. Grimmer and Zinn, Augmented Solar Energy collection using different types of planar reflective surface, Solar Energy, Vol. 21, 497-501, 1978.

12. John A. Duffie and William A. Beckman, Solar Energy Thermal Processes, A Wiley-Interscience Publication, 1974.

APPENDIX A

The general equation of the best fitting curve shown in Fig. 3.3.1 is found to be a fourth degree equation. This equation is generated in the computer package 'grapher' and it is given as:

$$W = a + b\,\theta + c\,\theta^2 + d\,\theta^3 + e\,\theta^4$$

where W is the thermal output energy of the collector in Watts, θ is the corresponding reflector angle from the horizontal, expressed in radians, and a, b, c, d and e are constants with values

$$\begin{aligned} a &= 283572 \\ b &= -854928 \\ c &= 961442 \\ d &= -476604 \\ e &= 87905 \end{aligned}$$

As an example let us take the case of a reflector angle, $\theta = 85^\circ = 85 \times \pi/180 = 1.4835$ radian.

$$\therefore W = 283572 - (854928 \times 1.4835) + (961442 \times 1.4835^2)$$
$$- (476604 \times 1.4835^3) + (87905 \times 1.4835^4)$$
$$= 921.6 \text{ W}$$

This is nearly equal to the observed value as recorded in Table 3.3.1 which is 921.2 W.